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AD-A213 846

Technical Document 1637
September 1989

Lidar Technique for Adjusting Aerosol Model Number Densities to Existing Conditions

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ADMINISTRATIVE INFORMATION

The study covered in this document was conducted from 30 September 1988 to 30 September 1989. It was funded under the auspices of the Office of Naval Technology under program element 62435N, project no. RM35G80, task no. 540-CDB6, and accession no. DN888715. The work is being performed by Code 543 of the Naval Ocean Systems Center (NOSC), San Diego, California.

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NOSC TD 1637	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Ocean Systems Center 6b. OFFICE SYMBOL (If applicable) Code 543	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) San Diego, CA 92152-5000	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Technology 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code) 800 N. Quincy Street Arlington, VA 22217-5000	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 62435N PROJECT NO.: RM35G80 TASK NO.: 540-CDB6 AGENCY ACCESSION NO.: DN888 715

11. TITLE (include Security Classification)

LIDAR TECHNIQUE FOR ADJUSTING AEROSOL MODEL NUMBER DENSITIES TO EXISTING CONDITIONS

12. PERSONAL AUTHOR(S)

H. G. Hughes, M. R. Paulson

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 30 Sep 88 TO 30 Sep 89	September 1989	22

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	aerosol extinction backscatter coefficients variations extinction coefficients variations single-scatter lidar equation backscattered power

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A technique is introduced by which the total number density of the LOWTRAN 7 (Kneisyz, et al., 1988) Navy Maritime Aerosol Model is adjusted to represent existing atmospheric conditions. Measurements of the vertical profile of relative humidity and surface wind speeds are used with the model to determine the aerosol extinction and backscatter coefficients variations with altitude. Using the single-scatter lidar (light detection and ranging) equation, these parameters are then used to calculate a range compensated power, S(h), from an airborne system. An iterative method is used by which the calculated S(h) values are adjusted to agree with corresponding measured values. Examples are presented of extinction and backscatter coefficients variations with range from the lidar calculated using adjusted size distribution. Also presented are the computer program and operating instructions for adjusting the size distributions at each altitude.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE PERSON H. G. Hughes	22b. TELEPHONE (include Area Code): (619) 553-1418 22c. OFFICE SYMBOL: Code 543

DD FORM 1473, 84 JAN

83 APR EDITION MAY BE USED UNTIL EXHAUSTED
ALL OTHER EDITIONS ARE OBSOLETE

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INTRODUCTION

Selectable aerosol size distribution models are now available in LOWTRAN 7 (Kneizys, et al., 1988) for calculating their scattering and absorption properties. Of primary interest here is the Navy Maritime Aerosol Model. This model was developed using an extensive set of broadband (visible through the far infrared) transmission measurements with simultaneous measurements of meteorological parameters, aerosol size distributions, and radon concentrations which were conducted in the Eastern Pacific (San Nicolas Island). Also included in the model's development were shipboard measurements (made in the Atlantic Ocean) of aerosol size distributions and meteorological parameters.

This model (see Appendix A) is the sum of three log normal size distributions. In addition to the surface wind speeds (current and 24-hour averaged) and relative humidity, the model requires the input of an air-mass factor which identifies the origin of the aerosols as either marine or continental. This input is allowed to range between integer values of 1 for open ocean conditions and 10 for coastal regions. Also, when an observed surface visibility is available as an input, the model is adjusted to make the visibility calculated at a wavelength of 0.55 μm the same as the observed value. The accuracy by which the model can predict infrared transmission (Gathman and Ulfers, 1983) and radiance (Hughes and Jensen, 1988) has undergone extensive evaluation. These studies have shown the model predictions to be sensitive to the selection of the air-mass factor and to whether the visibility was used as an input.

The model was developed to represent, as best as possible, the different atmospheric conditions; however, it cannot be expected to exactly reproduce the optical properties in a given location at any specific time. A method is needed for selecting the input parameters so that the model best represents a particular situation. A remote sensing technique has recently been developed (Hughes and Jensen, 1988) whereby unique values of the air-mass factor and visibility for different meteorological conditions are inferred from LOWTRAN calculations. These calculations agree with both the surface measurements of 8-12 μm horizon radiances and visible atmospheric optical depths determined from satellite-detected upwelling solar radiances over the ocean. However, this approach is limited to cloud-free sky conditions during the daytime and requires a favorable position of the satellite to avoid sun glint from the ocean.

An alternative approach is to model the backscattered power as a function of range from a calibrated visible or near infrared lidar system. Given the air-mass factor, the total number density of the model can be adjusted to allow the range-compensated power, calculated using the model, to match that measured by the lidar, i.e.,

$$S(R)_{meas} = S(R)_{cal} \tag{1}$$

where $S(R) = \ln[P(R)R^2]$, and $P(R)$ is the power received from the scattering volume at a range R. The single-scatter lidar equation is then given by

$$S(R)_{cal} = \ln(C) + \ln[k\beta(R)] - 2\int_0^R k\sigma(r)dr \tag{2}$$

where σ and β are the range-dependent volumetric extinction and backscatter coefficients, respectively, determined from the model using Mie theory, and C is the system constant. The factor k is then the multiplier of the size distribution which allows equation (1) to be satisfied.

Let us suppose that the lidar is aimed in a vertical direction and that the atmosphere is composed of layers at altitudes h_o, h_1, $h_3 \ldots h_N$. Expressing equation (2) in terms of altitude, h, then yields

$$S(h_n) = \ln(C) + \ln[k_n\beta(h_n)] - \sum_{n=0}^{N} \{[k_{n-1}\sigma(h)_{n-1} + k_n\sigma(h_n)][h_n - h_{n-1}]\} \qquad (3)$$

Equation (3) is solved by iteration to determine the k factor at each altitude based on the adjusted extinction and backscatter coefficients in the underlying layers. In the iteration for the k factor within the cross-over range between the receiver field-of-view and the laser beam (i.e., level 0 to 1), the extinction and backscatter coefficients are assumed to be that at level 1. The listing of the computer program for running on an IBM-compatible computer is found in Appendix B. This program is written in QUICK BASIC 4.5. In this report, the technique is demonstrated by using lidar measurements obtained from an aircraft, along with simultaneous measurements of meteorological parameters and size distributions.

MEASUREMENTS

For this study, a Piper Navajo aircraft, equipped with Rosemount temperature and pressure probes, and an EG&G dewpoint sensor, made a vertical spiral over the ocean to obtain the profile of relative humidity (figure 1) required by the Navy Maritime Aerosol Model. At the time the meteorological parameters were obtained on 30 March 1989, the current and 24 h averaged wind speeds (V_c = 4.9 m/s and $\bar{V}$ = 2.6 m/s) were measured on shore. From an altitude of of 1000 meters, a lidar mounted in the aircraft was aimed downward toward the ocean. The system employed in this study was the AN/GVS-5 rangefinder-based VISIOCEILOMETER which the U. S. Army Atmospheric Sciences Laboratory developed and is described elsewhere (Lindberg et al., 1984). Basically, the system is a Nd:YAG laser which nominally emits a 10 mJ, 6 ns pulse at a wavelength of 1.06 μm. The receiver telescope has an aperture of 5.1 cm with a 3 mrad field-of-view. The range at which the receiver field-of-view and the transmitter beam overlap is approximately 100 meters. A signal processing unit clocks the output of a silicon photo-avalanche detector at a 20 MHz rate giving a 7.5 m sampling interval. The digitized results are transferred to a microprocessor and then to a Memodyne cassette tape recorder for off-line processing. The system is calibrated within an accuracy of $\pm$ 5 percent.

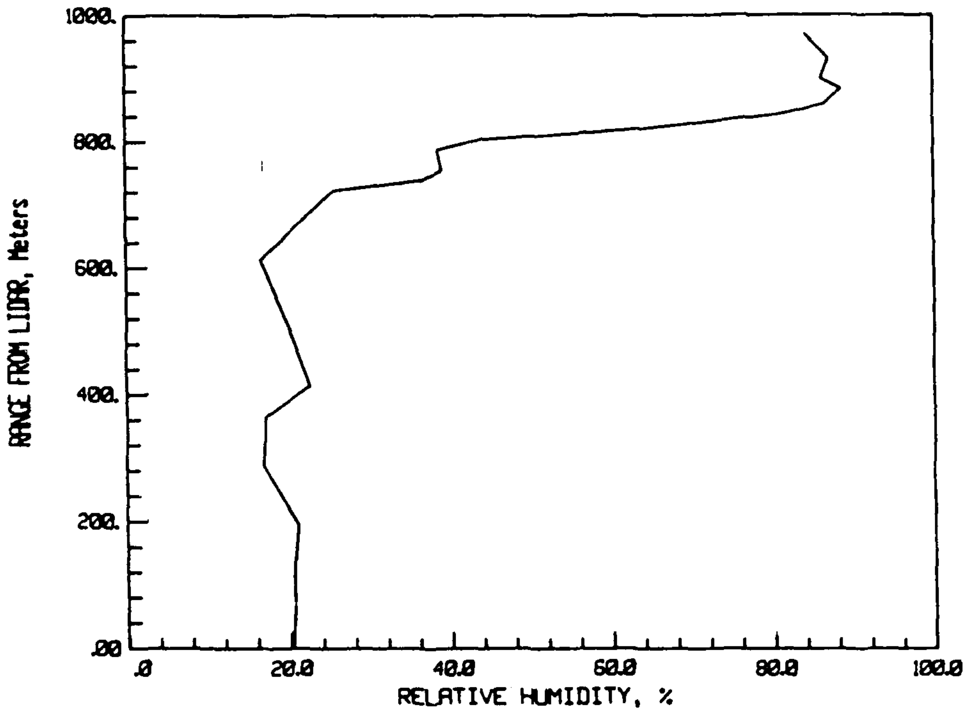

Figure 1. Relative humidity variation with range from the lidar.

MODEL ADJUSTMENT

Using the measured profile of relative humidity and surface wind speeds, the model was used with Mie theory to calculate the aerosol extinction and backscatter coefficients. Figures 2 and 3 show the variations of these two parameters with range from the lidar for air-mass factors (AM) of 1 and 8. The constant values between 100 meters and 804 meters are the result of the model defaulting to a minimum value of 50-percent relative humidity. Using the calculated extinction and backscatter coefficients, a range-compensated power, S(h), was calculated with range from the lidar for the two air-mass factors with the k-factor set to unity. In figure 4, the calculated S(h) values are compared with that measured by the lidar where the deficiencies of the unadjusted models are readily apparent. Figure 5 shows the k-factors required for the calculated values of S(h) to match the measured values within 0.1 percent. At ranges greater than about 800 meters within the mixed boundary layer, k-factors between 8 and 10 are required for the calculations using an air-mass factor of 1 to match the measurements. For an air-mass factor of 8, k-factors between 5 and 7 are required. Figures 6 and 7 show the extinction and backscatter coefficients determined using the adjusted models. It is interesting to note that the structures, which were absent in figures 2 and 3, now appear in both the extinction and backscatter profiles above the mixed layer.

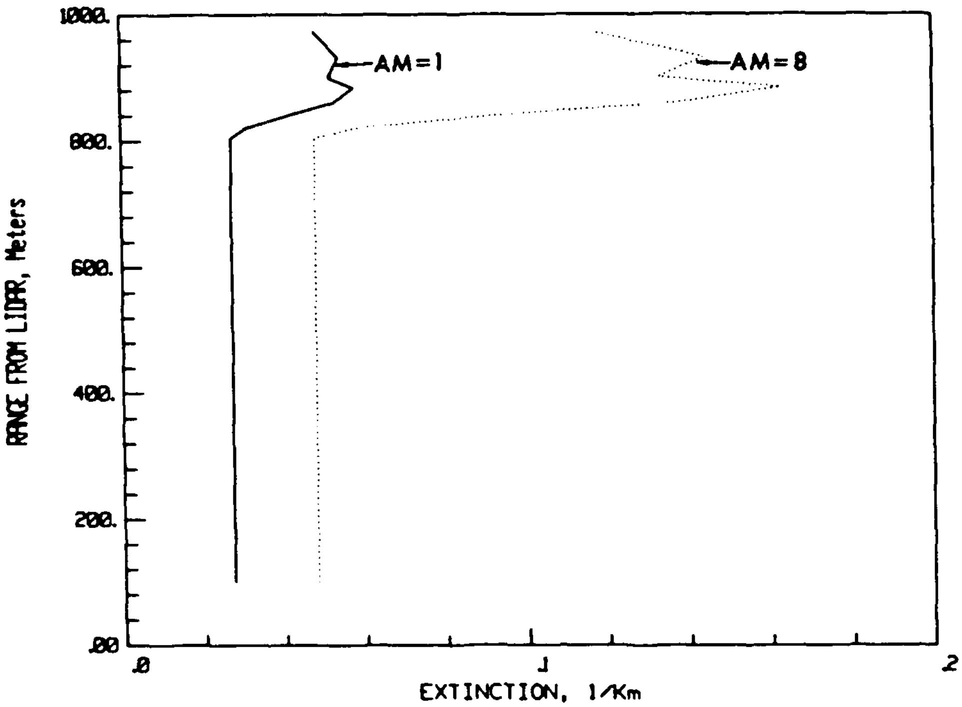

Figure 2. Extinction coefficient variation with range from the lidar calculated using the unadjusted aerosol model with air mass factors of 1 and 8.

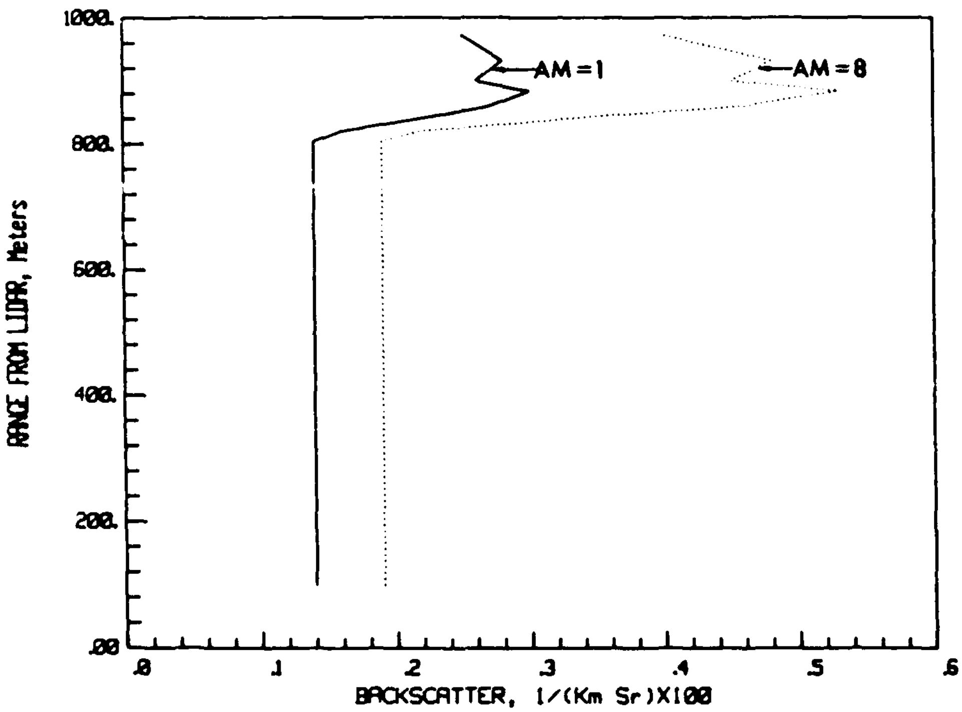

Figure 3. Backscatter coefficient variation with range from the lidar calculated using the unadjusted aerosol model with air mass factors of 1 and 8.

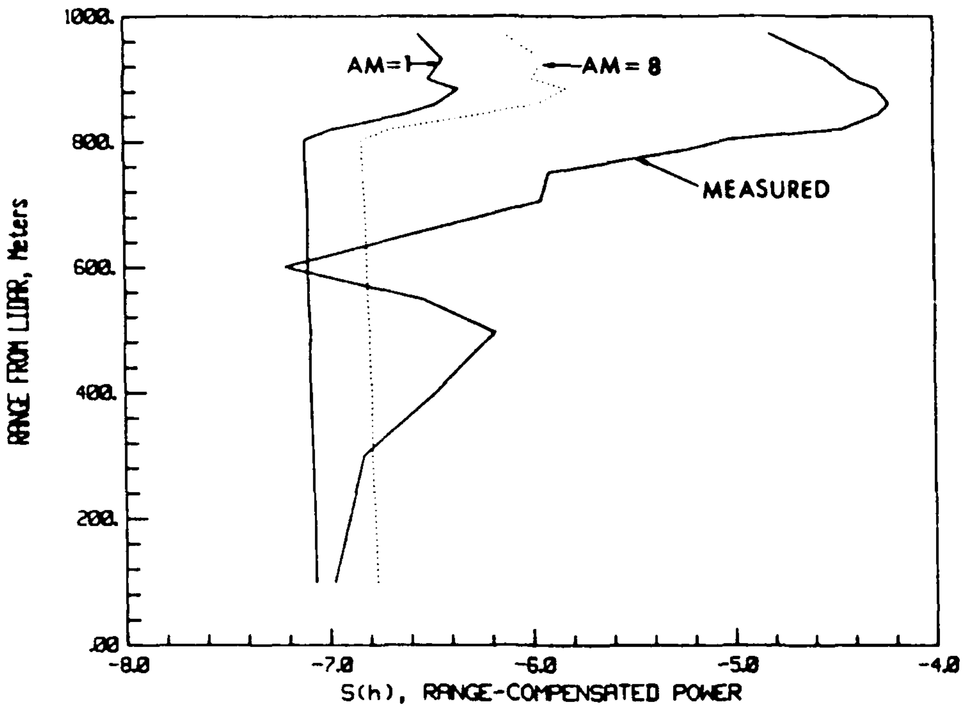

Figure 4. Comparison of the range compensated power calculated using the unadjusted aerosol models and that measured by the lidar.

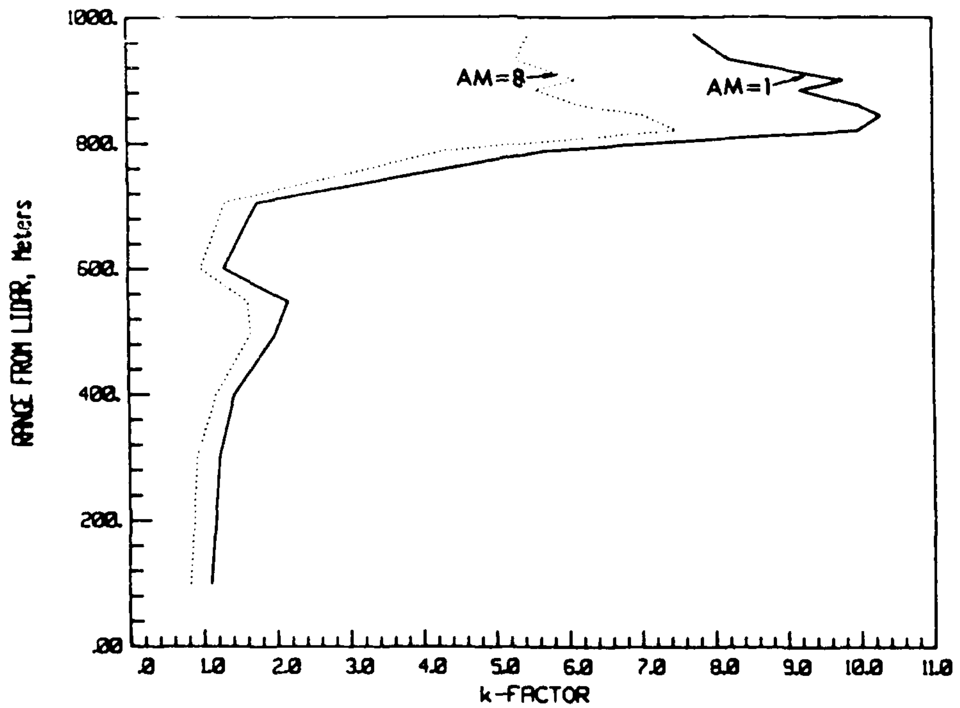

Figure 5. k-factors required for the calculated and measured values of S(h) to agree.

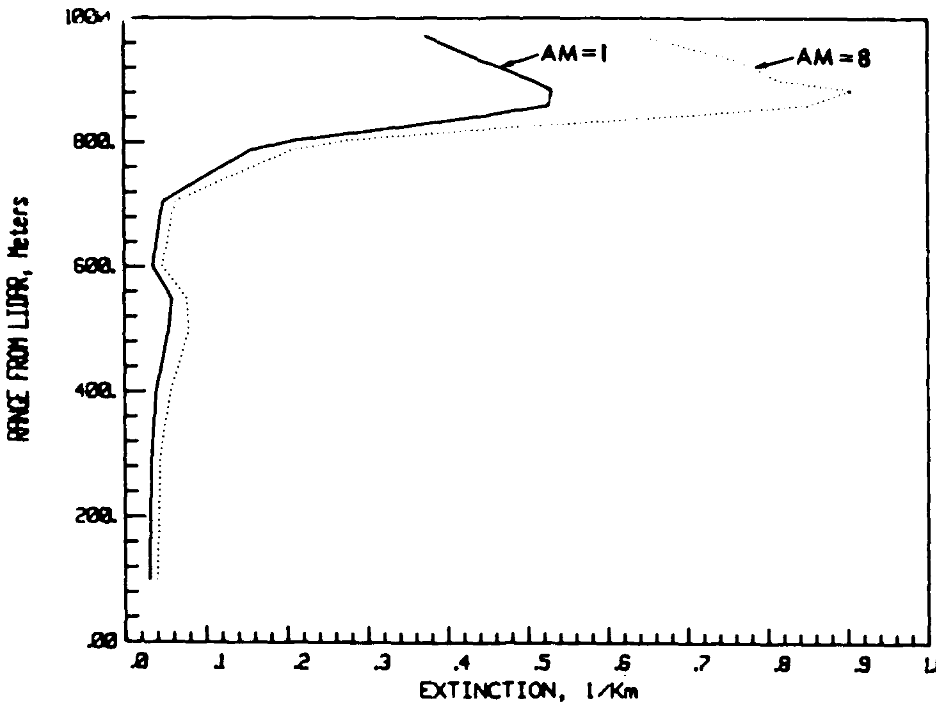

Figure 6. Extinction coefficient variation with range from the lidar calculated using the adjusted aerosol model with air mass factors of 1 and 8.

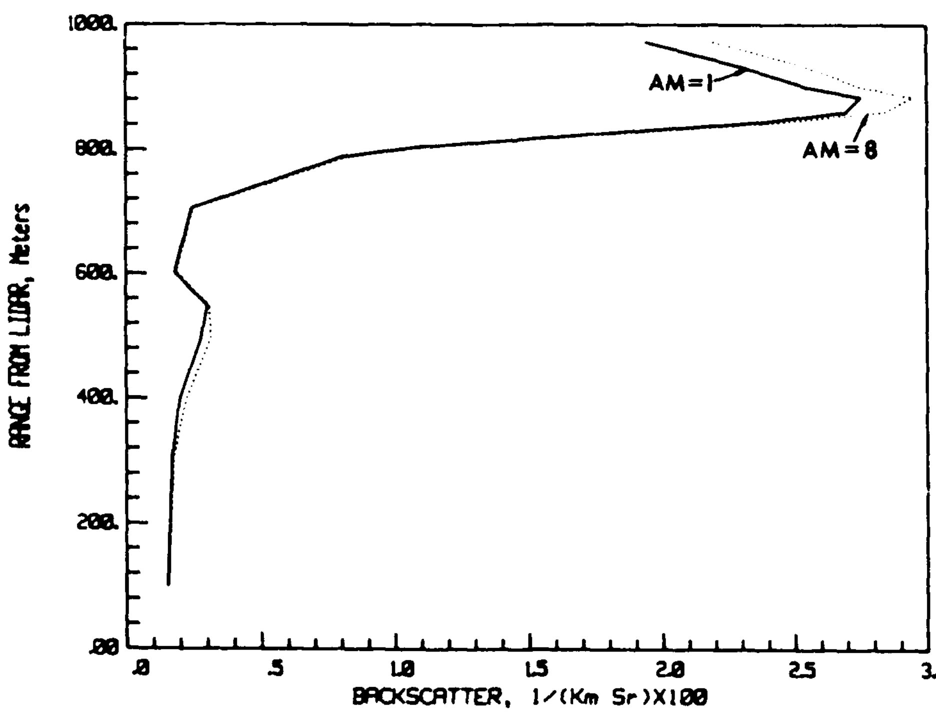

Figure 7. Backscatter coefficient variation with range from the lidar calculated using the adjusted aerosol model with air mass factors of 1 and 8.

DISCUSSION

This study has demonstrated that the k-factor needed to adjust the total number density of the aerosol model to existing atmospheric conditions can be determined from a single-ended lidar return. However, for the particular model examined, the air-mass factor must be known. In the absence of atmospheric radon concentration measurements or air trajectory analyses, the appropriate air-mass factor could be inferred by the model's ability to predict infrared sky radiances measured with elevation using the LOWTRAN 7 code. The technique would also be useful in adjusting aerosol size distributions measured with the commercially available Particle Measuring Systems size spectrometer probes (Knollenbergs).

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APPENDIX A: Description of the LOWTRAN 7 Navy Maritime Aerosol Model

The particle size distribution model (at radius r) is the sum of three log-normal distributions given by

$$n(r) = \sum_{i=1}^{3} A_i \exp\left[-\left(\ln \frac{r}{fr_i}\right)^2\right] \quad (cm^{-3} \cdot \mu m^{-1}) , \tag{1}$$

where

$$A_1 = 2000(AM)^2 , \tag{2}$$

$$A_2 = 5.866(\bar{V} - 2.2) , \tag{3}$$

$$A_3 = 10^{(0.06V_c - 2.8)} \tag{4}$$

Component A_1 represents the contribution by continental aerosols. AM is an air-mass parameter that is allowed to range between integer values of 1 for open ocean and 10 for coastal areas and is given by

$$AM = INT(Rn/4) + 1 , \tag{5}$$

where Rn is the measured atmospheric radon content expressed in pCi/m^3. In the absence of radon measurements, the air-mass factor can be related to the elapsed time, T(days), for the air mass to reach the point of observation:

$$AM = INT[9\exp(-T/4)] + 1 \tag{6}$$

Components A_2 and A_3 represent equilibrium sea-spray particles generated by the surface wind speed averaged over 24 h ($\bar{V}$, in m/s) and the current surface wind speed (V_c, in m/s), respectively. In equation (1), r_i, the modal radius for each component referenced to a relative humidity of 80 percent ($r_1 = 0.03\ \mu m$, $r_2 = 0.24\ \mu m$, and $r_3 = 2.0\ \mu$) is allowed to grow with relative humidity (RH), according to the Fitzgerald (1975) formula:

$$f = [(2 - RH/100)/6(1 - RH/100)]^{1/3} , \tag{7}$$

The contribution to the total extinction or absorption by each component can then be written as

$$\sigma_{e,a}(\lambda)_i = (SF)\left\{C_i \int_r Q_{e,a}(\lambda,r,m)\exp\left[-\left(\ln\frac{r}{fr_i}\right)^2\right] r^2 dr\right\} \tag{8}$$

Where $C_i = (0.001\pi/f)A_i$. The factor f^{-1} in the expression for C_i ensures a constant total number of particles as the relative humidity increases. $Q_{e,a}(\lambda,r,m)$ is the cross section for either the extinction or absorption normalized to the geometrical cross section of the spherical particle; and m is the complex refractive index, which is allowed to change from that of dry sea salt as the particle deliquesces with increasing humidity. LOWTRAN 6

APPENDIX B: Operating Instructions for a Computer Program to Adjust Aerosol Number Densities to Existing Conditions

The program uses extinction coefficients and backscatter coefficients measured or modeled as a function of altitude, and S(h) values as a function of altitude measured with the use of a lidar. It then calculates an adjustment factor for each altitude so that an S(h) calculated from the extinction coefficients and backscatter coefficients agrees with that measured by the lidar to within less than 0.1 percent.

These adjustment factors are then applied to obtain new, or adjusted, extinction and backscatter coefficient profiles as a function of altitude.

The input data are read from a disk file in the format shown in table 1. The first column is range in meters from the lidar. In the case when the lidar is in an aircraft pointed down, zero range would be at the altitude of the aircraft; and as range increased, the altitude would decrease. The second column is extinction coefficients in 1/km units corresponding to the ranges in column 1. The third column is backscatter coefficients in [1/(km sr)], and the last column is the S(h) values measured with the lidar.

Table B-1. Example of data input file format.

```
100,.0303,.00128,-6.979
200,.0332,.00175,-6.639
300,.0354,.00197,-6.834
400,.0483,.00190,-6.483
500,.0372,.00136,-6.184
600,.0359,.00092,-6.225
640,.0234,.00055,-7.078
700,.0534,.00168,-6.056
716,.0536,.00186,-6.073
764,.0556,.00173,-6.017
768,.0676,.00256,-5.107
810,.1410,.00427,-4.788
840,.5970,.02450,-4.268
878,.5570,.01870,-4.205
900,.4150,.01570,-4.409
924,.3330,.01270,-4.351
962,.3780,.01560,-4.671
```

The program asks if you want a printout of the results. If the answer is no, the output goes to the screen, otherwise it goes to the printer in the format shown in table 2. In the upper part of this table all of the original input data are printed along with the adjustment factor, k. In the lower part of the table, the adjustment factors have been applied to the extinction and backscatter coefficient profiles. The next to the last column gives a nominal visibility as a function of range; or altitude, if conditions had been horizontally homogeneous. The last column is a progressive summation of the adjusted extinction coefficient as a function of range.

The last question the program asks is if you want a graph. If the answer is yes, a graph of S(h) versus range is plotted. This option could be greatly expanded to plot any of the other parameters, if desired. A listing of the program follows.

Table B-2. Example of program output listing.

RNGE(m)	Extinction(km-1)	Beta	k	SofH
100	0.0303	0.00128	1.2101	-6.979
200	0.0332	0.00175	1.0801	-6.639
300	0.0354	0.00197	1.0401	-6.834
400	0.0483	0.00190	1.1676	-6.483
500	0.0372	0.00136	2.2876	-6.184
600	0.0359	0.00092	3.9401	-6.225
640	0.0234	0.00055	4.2451	-7.078
700	0.0534	0.00168	1.5251	-6.056
716	0.0536	0.00186	2.3001	-6.073
764	0.0556	0.00173	2.5401	-6.017
768	0.0676	0.00256	2.8001	-5.107
810	0.1410	0.00427	3.1776	-4.788
840	0.5970	0.02450	0.8663	-4.268
878	0.5570	0.01870	1.6001	-4.205
900	0.4150	0.01570	1.8476	-4.409
924	0.3330	0.01270	2.1951	-4.351
962	0.3780	0.01560	1.6501	-4.671

RNGE(m)	k*Extinction(km-1)	k*Beta	Vis(km)	ExtSum
100	0.0367	0.00155	106.69	0.00733
200	0.0359	0.00189	109.09	0.01094
300	0.0368	0.00205	106.25	0.01458
400	0.0564	0.00222	69.37	0.01925
500	0.0851	0.00311	45.97	0.02632
600	0.1414	0.00362	27.66	0.03764
640	0.0993	0.00233	39.38	0.04247
700	0.0814	0.00256	48.04	0.04790
716	0.1233	0.00428	31.73	0.04953
764	0.1412	0.00439	27.70	0.05589
768	0.1893	0.00717	20.67	0.05654
810	0.4480	0.01357	8.73	0.06992
840	0.5172	0.02123	7.56	0.08442
878	0.8913	0.02992	4.39	0.11122
900	0.7668	0.02901	5.10	0.12939
924	0.7310	0.02788	5.35	0.14740
962	0.6237	0.02574	6.27	0.17315

DATE : 07-31-1989 TIME : 07:40:02 Data File : B:aircraft

```
DECLARE SUB Graf (Ht!(), Sm!(), Nbr)
DECLARE SUB Xaxes (Xmin!, Ymin!, Xmax!, Ymax!)
DECLARE SUB Yaxes (Xmin!, Ymin!, Xmax!, Ymax!)
'**************************** SrMatch ******************************
'*        Program to match measured and modeled S(h) values.       *
'*                                                                 *
'* Uses extinction and backscatter coefficients as a function of   *
'* altitude calculated by the program MODEL. Looks for a factor, k, *
'* for each altitude such that, when the backscatter and extinction *
'* coefficients are multiplied by these k's an S(h) can be calc-   *
'* ulated for each altitude that agrees with that measured with a  *
'* LIDAR.              06/28/89   Revised 07/24/89  mrp            *
'*******************************************************************
OPTION BASE 1
DIM Ht(300), Beta(300), Ext(300), K(300), Sm(300), ExtSum(300)
DIM Vis(300)
CLS : COLOR 7, 1: CLS
start: PRINT "Do you want a printout? (Y/N or Q to quit) "
P$ = UCASE$(INPUT$(1))
IF P$ = "Q" THEN GOTO quit
PRINT "Enter Input Disk Drive "
Drv$ = UCASE$(INPUT$(1))
INPUT "enter input file name ", F$
datafile$ = Drv$ + ":" + F$
Lnc = -.5
PRINT "Do you want to store output on disk? Y/N  "
 Sd$ = INPUT$(1)
Sd$ = UCASE$(Sd$)
IF Sd$ = "Y" THEN
PRINT "Enter output Disk Drive "
Dout$ = UCASE$(INPUT$(1))
INPUT "Enter output file name ", Fout$
Fileout$ = Dout$ + ":" + Fout$
OPEN Fileout$ FOR OUTPUT AS #2
END IF

OPEN datafile$ FOR INPUT AS #1
ON ERROR GOTO errout
i = 1
DO UNTIL EOF(1)
INPUT #1, Ht(i), Ext(i), Beta(i), Sm(i)
PRINT "     "; Ht(i), Ext(i), Beta(i), Sm(i)
i = i + 1
LOOP
CLOSE #1
jout: Nbr = i - 1: PRINT TAB(25); Nbr; " levels"
h0 = Ht(1) / 1000: ext0 = Ext(1)
ExtSum(1) = 2 * h0 * ext0
Tmp = .1
k1 = .0001: Delta = .01: Ky = 1
DO UNTIL ABS(Tmp) < .001
Tmp1 = Sm(1) - Lnc
Tmp2 = LOG(k1) + LOG(Beta(1)) - k1 * ExtSum(1)
Tmp = Tmp1 - Tmp2
```

```
IF SignT <> SGN(Tmp) AND Ky <> 1 THEN Delta = -Delta / 2
SignT = SGN(Tmp)
kl = kl + Delta
Ky = 5
LOOP
K(1) = kl
ExtSum(1) = ExtSum(1) * K(1)
Vis(1) = 3.912 / (K(1) * Ext(1))
PRINT TAB(17); "Level     k          Error "
PRINT USING "                 ##     ##.######    #.####^^^^"; 1; K(1); Tmp
'<<<<<<<<<<<<<<<<<<<<<<< >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
FOR J = 2 TO Nbr
Tmp = .1
kl = .0001: Delta = .01: Ky = 1
DO UNTIL ABS(Tmp) < .001
K(J) = kl
GOSUB Sigma
Tmp1 = (Sm(J) + Sm(J - 1)) / 2 - Lnc
Tmp2 = LOG(kl) + LOG(Beta(J)) - 2 * ExtSum(J) - ExtSum(1)
Tmp = Tmp1 - Tmp2
IF SignT <> SGN(Tmp) AND Ky <> 1 THEN Delta = -Delta / 2
SignT = SGN(Tmp)
kl = kl + Delta
Ky = 5
LOOP
nxt: K(J) = kl
Vis(J) = 3.912 / (K(J) * Ext(J))
PRINT USING "                 ##     ##.######    #.####^^^^"; J; K(J); Tmp
NEXT J
'<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<< PrintOut >>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

IF P$ = "Y" THEN
  LPRINT "              RNGE(m)    Extinction(km-1)       Beta           k
 SofH"
  LPRINT "            ---------------------------------------------------------
------------"
  FOR L = 1 TO Nbr
    LPRINT USING "           #####          ##.####          ###.#####
##.####    ###.###    ###.###"; Ht(L); Ext(L); Beta(L); K(L); Sm(L)
  NEXT L
  LPRINT "            ---------------------------------------------------------
------------"
  LPRINT "              RNGE(m)   k*Extinction(km-1)  k*Beta      Vis(km)
ExtSum "
  LPRINT "            ---------------------------------------------------------
------------"
  FOR L = 1 TO Nbr
    LPRINT USING "           #####         ##.####         ###.#####
###.##    ##.#####  ##.#####"; Ht(L); K(L) * Ext(L); K(L) * Beta(L); Vis(L);
ExtSum(L)
  NEXT L
  LPRINT "            ---------------------------------------------------------
------------"
  LPRINT "              DATE : "; DATE$; " TIME : "; TIME$; " Data File : ";
datafile$
```

```
ELSE
  CLS
  PRINT "        ------------------------------------------------------------
--------"
  PRINT "        RNGE(m)    Extinction(km-1)     Beta          k        SofH"
  PRINT "        ------------------------------------------------------------
--------"
  FOR L = 1 TO Nbr
    PRINT USING "       #####          ##.#####            #.#####    ##.####
###.###"; Ht(L); Ext(L); Beta(L); K(L); Sm(L)
  NEXT L
  PRINT "        ------------------------------------------------------------
--------"
  PRINT "Press  c to continue"
  DO WHILE UCASE$(INKEY$) <> "C": LOOP
  PRINT "        ------------------------------------------------------------
--------"
  PRINT "        RNGE(m)    k*Extinction(km-1)  k*Beta    Vis(km)    ExtSum
 "
  PRINT "        ------------------------------------------------------------
--------"
  FOR L = 1 TO Nbr
    PRINT USING "       #####          ##.#####       ####.#####    ###.##
##.#####"; Ht(L); K(L) * Ext(L); K(L) * Beta(L); Vis(L); ExtSum(L)
  NEXT L
  PRINT "        ------------------------------------------------------------
--------"
  PRINT "        DATE : "; DATE$; " TIME : "; TIME$; "  Data File : ";
datafile$
END IF
PRINT
IF Sd$ = "Y" THEN GOSUB Dstore
PRINT "Do You want to graph S(R) data? Y/N"
G$ = UCASE$(INPUT$(1))
IF G$ = "Y" THEN CALL Graf(Ht(), Sm(), Nbr)
SCREEN 0: CLS
GOTO start
quit: PRINT "Program terminated by user"
END
errout:
IF ERR = 62 THEN
GOTO jout
ELSE
PRINT "Error No. "; ERR
END IF
END
Sigma:
SigSum = ExtSum(1)

FOR K = 2 TO J
SigSum = SigSum + (Ext(K) * K(K) + Ext(K - 1) * K(K - 1)) / 2 * (Ht(K) -
Ht(K - 1)) / 1000
NEXT K
ExtSum(J) = SigSum
RETURN
```

```
END

Dstore: '--------------------- Store Data on Disk ---------------------
  PRINT #2, "              ----------------------------------------------------
----------------"
  PRINT #2, "              RNGE(m)     Extinction(km-1)     Beta        k
 SofH"
  PRINT #2, "              ----------------------------------------------------
----------------"
  FOR L = 1 TO Nbr
    PRINT #2, USING "          #####        ##.#####          #.#####
##.####    ###.###"; Ht(L); Ext(L); Beta(L); K(L); Sm(L)
  NEXT L
  PRINT #2, "              ----------------------------------------------------
----------------"

  PRINT #2, "              ----------------------------------------------------
----------------"
  PRINT #2, "              RNGE(m)     k*Extinction(km-1)  k*Beta    Vis(km)
ExtSum    "
  PRINT #2, "              ----------------------------------------------------
----------------"
  FOR L = 1 TO Nbr
    PRINT #2, USING "          #####         ##.#####      ####.#####
###.##  ##.#####"; Ht(L); K(L) * Ext(L); K(L) * Beta(L); Vis(L); ExtSum(L)
  NEXT L
  PRINT #2, "              ----------------------------------------------------
----------------"
  PRINT #2, "              DATE : "; DATE$; " TIME : "; TIME$; "  Data File :
"; datafile$
CLOSE #2
RETURN
END

SUB Graf (Ht(), Sm(), Nbr)

SCREEN 0
COLOR 7, 1: CLS
INPUT "Xmin,Xmax,Ymin,Ymax ", Xmin, Xmax, Ymin, Ymax
CLS
SCREEN 9: CLS
VIEW (80, 30)-(590, 290)
WINDOW (Xmin, Ymin)-(Xmax, Ymax)
'COLOR 7, 1
LINE (Xmin, Ymin)-(Xmax, Ymax), 3, B
CALL Xaxes(Xmin, Ymin, Xmax, Ymax)
CALL Yaxes(Xmin, Ymin, Xmax, Ymax)
FOR J = 2 TO Nbr
   LINE (Ht(J - 1), Sm(J - 1))-(Ht(J), Sm(J)), 12
NEXT J
DO WHILE INKEY$ <> "c": LOOP
END SUB

SUB Xaxes (Xmin, Ymin, Xmax, Ymax)
Xstep = ABS((Xmax - Xmin) / 50)
```

```
Xtic = ABS(Ymax - Ymin) * .01: Xmtic = 2.2 * Xtic
J = 0

FOR X = Xmin TO Xmax STEP Xstep
IF J MOD 5 = 0 THEN
LINE (X, Ymin)-(X, Ymin + Xmtic), 3
ELSE
LINE (X, Ymin)-(X, Ymin + Xtic), 3
END IF
J = J + 1
NEXT X
COLOR 3
P0 = 7: Dx = 7: K = .2
FOR X = Xmin TO Xmax STEP 10 * Xstep
   IF X = Xmin THEN
      P = P0
   ELSE
      P = P0 + INT(K * Dx)
   END IF
   LOCATE 22, P
    PRINT USING "#####"; X
    K = K + 1.8
NEXT X
LOCATE 23, 36
PRINT "RANGE (Meters)"

END SUB

SUB Yaxes (Xmin, Ymin, Xmax, Ymax)
Ystep = (Ymax - Ymin) / 50
Ytic = ABS(Xmax - Xmin) * .01: Ymtic = 2.2 * Ytic
J = 0
FOR Y = Ymin TO Ymax STEP Ystep
IF J MOD 5 = 0 THEN
LINE (Xmin, Y)-(Xmin + Ymtic, Y), 3
ELSE
LINE (Xmin, Y)-(Xmin + Ytic, Y), 3
END IF
J = J + 1
NEXT Y
COLOR 3
P0 = 21: Dy = 4: K = .1
FOR Y = Ymin TO Ymax STEP 10 * Ystep
   IF Y = Ymin THEN
      P = P0
   ELSE
      P = P0 - INT(K * Dy)
   END IF
   LOCATE P, 6
   PRINT USING "####"; Y
   K = K + .9
NEXT Y
LOCATE 11, 2
PRINT "S(R)"
END SUB
```